Late Pleistocene-Holocene Transgressive Sedimentation in Deltaic and Non-Deltaic Areas of the Bering Epicontinental Shelf

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ABSTRACT

The distribution of late Pleistocene (>10,000 years BP)[1] and Holocene (≤10,000 years Bp) surface sediment on the northern Bering Sea floor is patchy and dependent upon locations of seafloor bedrock and pre-late Pleistocene glacial debris, late Holocene river sediment influx, and modern strong bottom currents. Seafloor vibracores and high-resolution profiles record two different sedimentary environments in the northern Bering shelf: late Pleistocene-Holocene shoreline transgression (≤16,000 years BP) in Chirikov Basin, and Holocene deposition from the Yukon River in Norton Sound.

Lag gravels remain exposed on the margins of Chirikov Basin where the transgression of the late Pleistocene-Holocene shoreline reworked pre-Quaternary bedrock and glacial moraines deposited during earlier low sea levels. The shoreline transgression over most of central Chirikov Basin left a cover of inner-shelf fine-sand facies that is underlain in places by a pebbly to medium sand basal transgressive facies, both of which overlie Pleistocene limnic peaty mud of emergent shelf deposition. Water circulation patterns have inhibited deposition of Holocene Yukon River silt over transgressive sand and lag gravels of Chirikov Basin.

About 9,500 BP, rapid marine transgression of Norton Sound began, to deposit a basal nearshore facies of thick storm-sand layers in marine silt overlain by an offshore bioturbated silt, both deposited over the Pleistocene freshwater peaty mud. Progradation of thick storm-sand layers and Holocene brackish-water silt deposits (up to 14 m) in southern Norton Sound is attributed to a shift of the present active Yukon delta lobe into its present position after about 2,500 BP.

Late Pleistocene and Holocene sedimentation on Bering shelf has implications for interpretation of ancient epicontinental shelf deposits. In Norton Sound, early Holocene transgressive sequences of coarser to fine muddy facies up-section are covered by regressive coarser facies in areas of deltaic progradation. In contrast, Chirikov Basin displays extremely thin transgressive deposits (<1 m) that are a complex mosaic of gravel, sand, and mud lenses unrelated to shoreline sources, just as sediment thickness is in parts of Norton Sound. Holocene sediments derived from the Yukon River bypass Chirikov Basin to accumulate hundreds of kilometers away in the Arctic Ocean in deposits averaging 10 m thick; however, thin accumulations (<2 m) occur in northern Norton Sound near the present Yukon Delta. In contrast to the complex transgressive sequences of the northern Bering shelf, the southern Bering shelf exhibits generally classic offshore gradation of coarse- to fine-grained Holocene deposits.

[1] For consistent stratigraphic nomenclature, deposits 10,000 years BP and younger are defined as Holocene in this paper (see Hopkins, 1975).

INTRODUCTION

The Bering epicontinental shelf is much like the North Sea shelf because of its strong currents (Cacchione and Drake, 1979) and numerous insular and peninsular constrictions. In addition, input of the Rhine and Elbe Rivers into the North Sea results in deltaic and non-deltaic areas of Holocene sedimentation (Nio et al., 1979) similar to those caused by discharge of the Yukon River on Bering shelf. On the northern Bering shelf during shoreline transgression of the late Pleistocene to Holocene, different transgressive sedimentary facies developed in the non-deltaic region of Chirikov Basin to the west and the deltaic area of Norton Sound to the east (Fig. 1). Definition of these two types of transgressive sedimentation in the Bering epicontinental shelf region provides important information to compare with similar deposits in other areas, like the North Sea, and to distinguish similar facies in ancient analogs.

The extremely thin transgressive sandy facies of the Chirikov Basin is described in this paper and compared to the thick, muddy sequence of Yukon-derived Holocene deposits in Norton Sound. In these different environments, the general lithology, sedimentary processes, and sedimentary history are outlined throughout the late Pleistocene and Holocene time. The present distribution of transgressive late Pleistocene and Holocene deposits is also explained in terms of modern oceanographic processes. Sediment distribution patterns and processes of northern Bering shelf are then compared to the overall patterns of epicontinental shelf sedimentation in the eastern Bering Sea. In the geologic significance section description of these highly variable sediment facies patterns on Bering shelf is used to provide new insights for the interpretation of similar ancient shelf deposits.

METHODS

The summary of late Pleistocene and Holocene history of sedimentation on the northern Bering shelf spans a decade of marine geologic research by the U.S. Geological Survey in this region. The findings in this paper are based on box cores and vibracoring up to 6 m into the seafloor and on more than 10,000 km of tracklines covered by high-resolution sparker, Uniboom, and 3.5-kHz continuous seismic profiling systems. Nearly 50 vibracores and 250 box cores have been described from lithologic analyses, X-ray radiography and epoxy peels. Samples also have been analyzed for texture, microfauna, and radiocarbon dates (see also McDougall, this volume).

OCEANOGRAPHIC SETTING

The northern Bering Sea is a very shallow epicontinental shelf area (<60 m deep) that can be divided into two provinces, Chirikov Basin and Norton Sound (Fig. 1). The shallow eastern half of the area, the Norton Sound embayment, is generally less than 20 m deep (Fig. 1). The very shallow prograding Yukon Delta wedge in southern Norton Sound is an important morphologic feature of Norton Sound that influences wave and storm-surge processes in this region. The western region, Chirikov Basin, is surrounded by projecting land masses on the northwest and northeast, and the large St. Lawrence island on the south that constrict and reinforce the strong geostrophic current flow (Fig. 1).

The Bering shelf, like that of the North Sea, is dominated by currents. Whereas all the North Sea shelf is strongly tidal, *only* the north part of Norton Sound is dominated by tidal currents; Chirikov Basin is influenced mainly by the strong northward geostrophic current (Fig. 1) (Cacchione and Drake, 1979). Currents are intensified along the eastern Bering Sea margin wherever land projects westward into them. Even more important is the increase in geostrophic current speeds, which have been observed to double, during moderate storm events (Cacchione and Drake, 1979; Schumacher and Tripp, 1979). As in the North Sea, storm-surge set-up along the Alaskan coast results in storm-related currents that cause major sedimentation events (Nelson, 1977).

GEOLOGIC BACKGROUND

A number of past eustatic sea-level changes determine distribution of the present Holocene and late Pleistocene shelf deposits. The most important influence, the last late Pleistocene and Holocene transgression, began about 12,000 to 13,000 years ago in straits where the water was deepest (Hopkins, 1973). At first a narrow seaway developed from Anadyr Strait to Bering Strait (Hopkins, 1979) and then from Shpanberg Strait to Bering Strait (Nelson and Creager, 1977). The narrow seaways expanded southeastward to fill out the deeper western area of Chirikov Basin until about 10,000 years ago. During shoreline transgression in Chirikov Basin a number of stillstand features were created. For example, ancient shorelines remain as large submerged sand ridges between King Island and Port Clarence (Figs. 2 and 3, B-B'), (see Nelson et al., this vol.), and recognizable ancient strandlines occur in numerous other locations, particularly off Nome (Nelson and Hopkins, 1972; Hopkins, 1973).

The entire Norton Sound region remained emergent until about 10,000 years ago. Sea-level fluctuations determined elsewhere (Field et al., 1979) and radiocarbon dates in Norton Sound show that from 10,000 to 9,500 years B.P., the shoreline rapidly transgressed eastward over Norton Sound, and buried tundra peat deposits.

The transgressing shoreline planed over a number of previous alluvial, glacial, and bedrock exposures. Bedrock remains exposed on the seafloor in regions near insular and peninsular granitic stocks and volcanic outcrops, such as near Cape Prince of Wales, King Island, and off northern St. Lawrence Island (Fig. 4) (Nelson and Hopkins, 1972). Another extensive area of sea floor bedrock occurs north of a major fault scarp (Johnson and Holmes, 1978) along the subsurface channel west of Port Clarence (Fig. 4) to the Cape Prince of Wales shoreline, and is perhaps correlative with Precambrian to Paleozoic limestone of the adjacent shoreline area (Nelson and Hopkins, 1972).

Numerous subsurface alluvial channels covered by the transgressive deposits have been mapped in the Norton Sound region where the most detailed grid of seismic profiles is present (Fig. 4). In Chirikov Basin the limited grid of seismic profiles (Fig. 2) does not permit detailed mapping of the subsurface channels, but major subsurface channels are known to exist west of Port Clarence, extending toward Bering Strait, and in the sea valley extending south from King Island (Hopkins et al., 1976) (Fig. 4).

Early and middle Pleistocene continental glaciation extending off (U.S.S.R.-Chukotka) to central Bering Sea, and local valley glaciation offshore from Seward Peninsula have been determined both by seismic profiling and by sediment sampling (Grim and McManus, 1970; Nelson and Hopkins, 1972; Tagg and Greene, 1973; Hopkins, 1975 and 979). The glacial moraines extend in the subsurface of the central Chirikov Basin and emerge toward land as gravel ridges (Figs. 4 and 5A). Complete sequences of moraines and outwash were documented in the nearshore areas off Nome from detailed profiling (Tagg and Greene, 1973) and drillholes as deep as 75 m below the seafloor (Nelson and Hopkins, 1972).

The other major geologic event that significantly influenced the distribution of late Pleistocene and Holocene deposits is the change in position of the active Yukon delta lobe on the Bering shelf. About 16,000 years ago, the Yukon River apparently crossed the present Bering shelf in the vicinity of Cape Romanzof and deposited a deltaic sequence south of St. Lawrence Island (Knebel and Creager, 1973a). As sea level rose in the the early Holocene, various active lobes developed far south of Norton Sound in the Black subdelta and Cape Romanzof regions (Fig. 1) (Nelson and Creager, 1977). The present active delta lobe first developed in southern Norton Sound after 2,500 years BP as shown by dating of onshore delta deposits (Dupré, this volume) and of offshore change from marine to brackish-water fauna (see core C in Fig. 3, A-A′) (McDougall, this volume). Since then the Yukon River has prograded significantly into Norton Sound and altered biological activity and attendent bioturbation patterns (Nelson et al., in press; Howard and Nelson, this volume).

LATE PLEISTOCENE TRANSGRESSIVE SEDIMENTATION IN CHIRIKOV BASIN

Transgressive Deposits

The late Pleistocene to Holocene shoreline transgression deposited a thin sequence of transgressive deposits on the margins of Chirikov Basin. On some margins, only a thin gravel lag is found over bedrock outcrops or glacial deposits (Fig. 3, B-B′, core D, and Figs. 4 and 5B). On other margins, the typical sequence is late Pleistocene freshwater peaty silt overlain by transgressive sand (Figs.3, B-B′ and Fig. 5B). The Pleistocene peaty silt occurs near the seafloor in troughs between sand ridges where strong bottom currents have either prevented deposition or have scoured through the transgressive sand into . the peaty mud (Fig. 3, B-B′, King Is. shoal to Port Clarence). The presence of very old radiocarbon dates from peaty mud in some trough locations suggests that significant scour has taken place there.

A typical trough sequence is fine sand above medium-grained sand overlying the peaty freshwater silt (Fig. 3, B-B′). An example of a complete eustatic cycle in northeastern Chirikov Basin is found in Core No. 247, taken between Tin City and York shoal (Figs. 3, B-B' and Fig. 5B). At the very base, a thin layer of coarse-grained regressive sand containing a fauna typical of cold, brackish water (P. Valentine, U.S. Geological Survey Woods Hole, 1976, written commun.) is overlain by a 20-cm-thick sequence of freshwater mud (McDougall, this volume) cut into by sand-filled burrows of marine clams. Above this is medium sand showing good trough cross-lamination that in turn is overlain by flat-laminated to massive fine sand (Fig. 5B).

The different transgressive gravel and sand facies exhibit an areal pattern related to underlying older deposits. The thin gravel lags are found close to shore over bedrock and parallel to emergent seafloor moraines that project into central Chirikov Basin south from Cape Prince of Wales and north from St. Lawrence Island (Fig. 3, B-B', Core D and Figs. 4 and 5A). offshore from the bedrock gravel lag of Seward Peninsula, medium-grained sand fringes the northeastern edge of Chirikov Basin (Fig. 6). The surface of central and southern Chirikov Basin is covered by fine sand that overlies the medium sand or late Pleistocene freshwater muds (Figs. 3, B-B', and 5B and C).

Transgressive History

The oldest deposits in Chirikov Basin are the gravel lags that occur over bedrock and pre-late Pleistocene glacial deposits (Fig. 6). These lags developed as the late Pleistocene-Holocene transgessive shoreline reworked bedrock or glacial deposits, removed fine-grained sediment and left a gravel lag deposit over their surface (Nelson and Hopkins, 1972). In places, the lags are much better rounded, contain higher percentages of quartz, and exhibit modes of medium- to coarse-grained sand, all of which indicate late Pleistocene-Holocene stillstands of the strand line at these particular depths of 10-12 m, 20-24 m, 30 m, and 38 m (Nelson et al., 1969; Nelson and Hopkins, 1972; Hopkins, 1973).

At locations where topographic elevations of bedrock and glacial moraines were not present, late Pleistocene tundra and freshwater silt with occasional alluvial deposits developed (Figs. 3 and 4). As the shoreline transgressed over the freshwater peaty mud of the once emergent seafloor, a basal coarse- to medium-grained sand, only a few centimeters thick, was deposited and remains uncovered in northern Chirikov Basin (Fig. 6). A fine-grained, inner shelf sand (Nelson et al., 1969) was laid down immediately off the shoreline as it transgressed; this generally overlies the basal coarser sand facies and forms a blanket deposit now covering most of the surface of central and southern Chirikov Basin (Fig. 6). The few vibracores from central Chirikov Basin suggest that this inner-shelf sand facies is no more than a few tens of centimeters thick (Fig. 3, B-B', cores E and F). The mineralogy and texture of this sand contain no evidence of the modern Yukon River sediment source (McManus et al., 1974). Thus, the Yukon sediment entering this region during the Holocene has bypassed northward to deposit in southern Chukchi Sea (Nelson and Creager, 1977) and no Holocene sediment is found in Chirikov Basin, except for that temporarily ponded in the troughs between sand ridges (Fig. 3, B-B').

HOLOCENE SEDIMENTATION IN NORTON SOUND

Holocene Deposits

As in much of Chirikov Basin, freshwater late Pleistocene silt and interbedded peat or peaty mud is the oldest stratigraphic unit observed in Norton Sound (Fig. 3, A-A'). Overlying the freshwater peaty mud is marine sandy silt with interbedded very fine sand layers in the southern Norton Sound region and deeper parts of the Holocene section in central Norton Sound. Above this sequence in central Norton Sound and throughout the northern area is bioturbated sandy silt derived from the Yukon River (McManus et al., 1977) (Howard and Nelson, this volume).

From onshore to offshore, the interbedded sand beds become finer grained, thinner, contain a smaller percentage of graded sand layers, and exhibit less complete sequences of vertical sedimentary structures (Nelson, 1977) (Fig. 5E and F). Nearshore, the graded sand layers make up 50-100% of the total sedimentary section; they range from 10 to 20 cm in thickness and have a mean grain size of about 0.250 mm in the coarsest part of the layer (Fig. SE) (also see Fig. 4G of Nelson et al., this volume). At the outer extremity of the distribution of interbedded sand layers, usually 60 to 75 km from the Yukon Delta shoreline, the graded sands are generally 1-2 cm thick, make up less than 35 percent of the total section, and have mean grain sizes of 0.125 mm or less (Fig. 5F).

The surficial Holocene deposits in Norton Sound vary from fine-grained sand surrounding the delta and trough along northern Norton Sound to very fine sand and coarse silt in central and eastern Norton Sound (Fig. 6) (see Fig. 3 of Howard and Nelson, this volume). Not only is sediment coarser in the northern trough, but the mineralogy also shows a mixed derivation from Seward Peninsula and Yukon River sources (McManus et al., 1974). Bioturbated mud is present in the surface of most of Norton Sound (Fig. 5F), except surrounding the modern Yukon subdelta where fine to very fine sand layers may be present at the surface (Nelson, 1977) (Fig. 5E).

Holocene Transgressive and Deltaic History

In contrast to the thin transgressive sequence of sand deposited in Chirikov Basin, Norton Sound contains a thin to thick blanket of Holocene silt and interbedded sand layers derived from the Yukon River. Thick sections of Holocene sediment have been deposited in southern Norton Sound because of progradation of the Yukon delta; only 2 m or less of bioturbated mud has been deposited in the more distal areas of northern and eastern Norton Sound

(Fig. 4B). The bathymetric trough in northern Norton Sound is an exception that appears to be an area of nondeposition through the Holocene because of tidal current flushing in the trough (Figs. 1 and 6) (Cacchione and Drake, 1979). Coarser texture than Yukon deposits (Fig. 6) and mineralogic origin from Seward Peninsula (Fig. 6) (McManus et al., 1974) suggests that Holocene trangressive sand remains in the tidally scoured trough. Elsewhere, Yukon mud with marine fauna has been deposited directly over late Pleistocene freshwater silt, and basal transgressive sand is not found as it is in Chirikov Basin (Fig. 3, A-A'). Although late Pleistocene alluvial deposits are shown incising the freshwater silt in seismic profiles, these deposits have not been identified in cores. Thick nearshore sand layers at depth (Fig. 3, A-A', core G), in central Norton Sound, however, suggest that the transgressive shoreline was close to this location early in Holocene Time. As the shoreline transgressed, deposition of the interbedded nearshore sand ceased, resulting in sedimentation of the upper sequence of offshore massive silt without interbedded sand (Fig. 3, A-A', core G, and Fig. 7).

Just as transgression of the shoreline is evident in the lower Holocene stratigraphy of central Norton Sound, migration of the active Yukon delta lobe from the Cape Romanzof region (Knebel and Creager, 1973a; Dupré, this volume) into southern Norton Sound and progradation of brackish-water delta deposits is evident in the upper Holocene stratigraphy of the Sound. When the delta shifted to its present position after 2500 BP (Fig. 3, A-A', core C) (Dupré, this volume), influx of low-salinity water into southern Norton Sound caused a change in fauna (see McDougall, this volume) and fluctuation in the rate of bioturbation, so that well-bioturbated mud was locally overlain by unbioturbated sequences of sand and interbedded mud (Fig. 3, A-A', core C, and Fig. 5D) (Nelson and Creager, 1977). Progradation of the active delta wedge with

with its unbioturbated sequences of thick sand layers fnterbedded in silt is shown in all upper Holocene sequences surrounding the delta (Fig. 3, A-A', cores C, H, I, Figs. 5, D-F, and Fig. 7) (Howard and Nelson, this volume; Nelson et al., in press). The vertically and horizontally graded sand layers in the near-surface sediment off the Yukon Delta appear to be prograding sand sheets deposited by currents (Cacchione and Drake, 1979; Schumacher and Tripp, 1979) associated with large-scale storm surge that occurs in Norton Sound (Nelson, 1977; Nelson and Creager, 1977).

Resuspension and removal of large quantities of Yukon sediment from Norton Sound (Fig. 8) by storm-related currents is another significant factor throughout Holocene depositional history. When the estimated discharge of Yukon sediment for the Holocene is compared with the isopach thickness of Holocene sediment in Norton Sound (Fig. 4B), about half of the estimated sediment introduced into Norton Sound is missing, but is found in a 10-m-thick blanket of Holocene mud in the southern Chukchi Sea (Fig. 9) (Nelson and Creager, 1977). Effects of the extensive storm resuspension of sediment are shown by the old radiocarbon dates yielded by modern surface mud (Figs. SD and 3, A-A', core I) and the pebble and shell lags found within the bioturbated mud (Fig. 5F). The lag layers are produced by storm-wave and current reworking of sediment to concentrate the coarser fragments from the resuspended mud. New evidence for this resuspension process has recently been acquired in central Norton Sound by *in situ* sediment dynamic and current meter probes (GEOPROBE) that showed several hundred percent increase in suspended sediment transport during a moderate storm event (Cacchione and Drake, 1979).

GEOLOGIC SIGNIFICANCE OF BERING SHELF FACIES PATTERNS

Comparison of the Chirikov Basin and Norton Sound regions shows that strong currents have influenced late Pleistocene and Holocene deposition in both regions. The strong currents and lack of sediment input into Chirikov Basin have resulted in a transgressive sand sequence that has no Holocene mud over it. Instead, on the northeastern margin of Chirikov Basin, non-deposition and/or scour have taken place so that in nearshore areas, where maximum geostrophic current shear occurs (Fig. 1), the basal coarse-sand facies remains exposed on the seafloor; farther inshore only bedrock outcrops with gravel lags are present (Fig. 6 and 8). Topographic elevations projecting upward into currents in this region (1) retain relict gravel lags over glacial or bedrock outcrops or (2) contain basal sands that are reworked into large-scale mobile bedforms (see Figs. 4C and H and Fig.5 of Nelson, et al., this vol.)

Offshore from the inshore bands of gravel and basal transgressive sand facies in northeast Chirikov Basin (Fig. 8), a parallel band of transgressive inner shelf sand occurs where the geostrophic current flow becomes considerably weaker to the west (Fig. 1). Although the surface sediment patterns of increasing coarseness inshore (Fig. 8) parallel those of increasingly stronger geostrophic current flow toward the northeast side of Chirikov Basin (Fig.1), the shore-parallel facies patterns in these areas could suggest equilibrium with offshore to inshore gradients of increasing wave energy. However, the sheltering and limitation of fetch by St. Lawrence Island, plus the occurrence of an inshore mud blanket parallel to the Port Clarence coastline (Fig. 8), eliminate wave energy as a possible cause of the shore-parallel transgressive facies.

The region west of the modern Yukon subdelta in Shpanberg Strait is another area of strong geostrophic current shear that has important implications for the facies distribution (Fig. 1). The southwest distributary discharges most of the Yukon River sediment load at this location, and parallel banding of sediment facies patterns develops. Here, fine-grained deposits are found closer to shore near the sediment source and become progressively coarser toward the center of the strait (Fig. 8). McManus et al. (1974) suggested that the central part of the strait is underlain by an older transgressive sand deposited in the narrow early Holocene seaway that extended from a more southerly Yukon Delta source in central Bering Sea (Knebel and Creager, 1973a) to Bering Strait. Therefore, sediments become increasingly coarser grained offshore where current erosion prevents prograding of modern fine sand and silt deposits over the coarse-grained, older transgressive sand.

Comparison of the current-dominated deposition of northern Bering Sea with sedimentation in the central Bering shelf shows the following. Just south of St. Lawrence Island, inner shelf sand like that in Chirikov Basin is present (Fig. 9) (Knebel and Creager 1973a and b; Knebel et al., 1973). Progressively to the south, and toward the edge of the shelf, surface sediment becomes finer grained, and a prograding mud blanket beginning in the mid-central shelf area extends as an increasingly thick wedge to the edge of the continental shelf; an exception is an area where islands are surrounded by coarse-grained relict deposits (Fig. 9).

Studies of Sharma et al. (1972) and Gardner et al. (in press) show that from the Bristol Bay shoreline out toward the shelf edge of southern Bering Sea, deposits become increasingly fine grained. In contrast to the northern Bering shelf, where deposition has been completely dominated by strong bottom current regimes a classic wave-graded pattern of sediment size distribution has developed on the epicontinental shelf in southern Bering Sea (Fig. 9).

The extreme variance of Holocene sedimentation patterns within single epicontinental shelf depositional systems like those of the Bering and North Seas has important implications for studies of ancient analogs. Epicontinental shelf deposits may be classically wave graded from the shoreline out in one part of a shelf and show similar gradations that are in equilibrium with offshore current regimes in nearby areas (Fig. 9). A major sediment source may reverse the normal onshore– to- offshore facies pattern and lithology of transgressive sequences in two adjacent regions of an epicontinental shelf like Chirikov Basin and Norton Sound (Fig. 8). Norton Sound and related southern Chukchi Sea deposits show that large quantities of sediment introduced into one part of Bering shelf are removed and displaced by currents from storms and related geostrophic circulation to create a major depocenter hundreds of kilometers from the source in another shelf area (Fig. 9) (Nelson and Creager, 1977). Thus, contrary to stratigraphic concepts, prograding prodelta deposits may be extremely thin on the shelf close to a major river source, yet thick hundreds of kilometers from the source; also they may grade from fine to coarse-grained proceeding offshore because of geostrophic current patterns. On the other hand, in normal transgressive sequences, onshore to offshore gradation to finer sediment may occur because geostrophic currents strengthen shoreward rather than as usually expected because of increasing wave energy shoreward (Fig. 8).

Analysis of Holocene sedimentation on Bering shelf has important implications for stratigraphic analysis in similar ancient sequences. Because of the local influence of deltaic sedimentation, currents and topography, areas of transgressive (Chirikov Basin) and regressive (Norton Sound) deposits may develop and coexist in the same area during rising sea levels. In a broad epicontinental shelf area like Chirikov Basin with no prograding delta, the rapid shoreline transgression and strong geostrophic currents result in thin late Pleistocene and Holocene transgressive basal and inner shelf sands without deposition of an overlying offshore mud sequence (Figs. 3 and 6). In inshore regions of strongest currents only thin basal transgressive lags may occur because finer grained offshore facies have been stripped off (Fig. 6).

In contrast to thin transgressive sand sequences of Chirikov Basin, in Norton Sound a thick sequence consisting of transgressive mud and interbedded nearshore storm sands, covered by offshore bioturbated mud is in turn overlain by a regressive sequence of thicker storm sands in mud deposited by the prograding delta in the late Holocene (Figs. 3 and 6).

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Figure Captions

Figure 1. Northeastern Bering Sea and southern Chukchi Sea, showing water circulation, maximum measured bottom-current velocities, and bathymetry. Modified from Nelson and Creager (1977) including new long-term in situ current measurements from Cacchione and Drake (1979) and R. Muench (written commun., NOAA-PMEL, Seattle, Wash., 1979).

Figure 2. Location of sampling stations and geophysical tracklines for U.S. Geological Survey research in northern Bering Sea between 1967 and 1978. Lines A-A′ and B-B′ show locations of cross-sections shown in Figure 3. Single letters A-F show station locations of core photographs in Figure 5.

Figure 3. Near-surface late Pleistocene and Holocene stratigraphy in Chirikov Basin (B-B′) and Norton Sound (A-A′) (see Fig. 2 for locations). Corrected dates with stars are calculated by the method shown in Figure 5D. In profile A-A′ the date of 1500 years BP in core C approximately dates freshwater influx of the modern Yukon delta lobe. In profile B-B′, the region of sand ridges in northeast Chirikov Basin extends from King Island shoal to Port Clarence.

Figure 4. A. Elements of pre-transgressive geologic history in northeastern Bering Sea showing locations of seafloor and near-surface bedrock outcrops, glacial moraines, and alluvial channels. Details of subsurface channels are incomplete, particularly in Chirikov Basin, because of insufficient geophysical trackline coverage. Information on glacial moraines is based on Nelson and Hopkins (1972) and on bedrock outcrops and subsurface channels is modified from Devin Thor (written communication, 1979).

B. Thickness of Holocene sediment based on seismic profiles (modified from Nelson and Creager, 1977) (Devin Thor, written communication, 1979).

Figure 5. Internal sedimentary features of late Pleistocene and Holocene deposits in northeastern Bering Shelf. Numbers to the left in B and C show percent of gravel and coarse to medium sand in transgressive and regressive sand layers. See Figure 2 for core locations.

A. Transgressive lag gravel over glacial till shown in a box core slab face. 41 m water depth.

B. Box core no. 247 radiograph showing cross-laminated transgressive fine-grained inner shelf sand overlying limnic clays with freshwater ostracodes (P. Valentine, written commun., U.S.G.S. Woods Hole, Mass., 1971). Note deep pelecypod burrowing into freshwater mud after the marine transgression. 36 m water depth.

C. Box core slab showing transgressive inner shelf fine sand overlying basal transgressive medium to fine sand. 48 m water depth.

D. Radiograph of cross-laminated and wavy bedded sand layers (light colored) in late Holocene Yukon silt (<5,000 years old) based on bulk sample radiocarbon dates (corrected for surface sample age) underlain by bioturbated older Yukon silt (>5,000 years old) (after Nelson and Creager, 1977). Located 75 km from the Yukon Delta in 16 m water depth.

E. Box core slab face showing a surface and a deeper bioturbated sand layer (light colored) in Yukon silt 30 km from the modern Yukon subdelta. 11 m water depth.

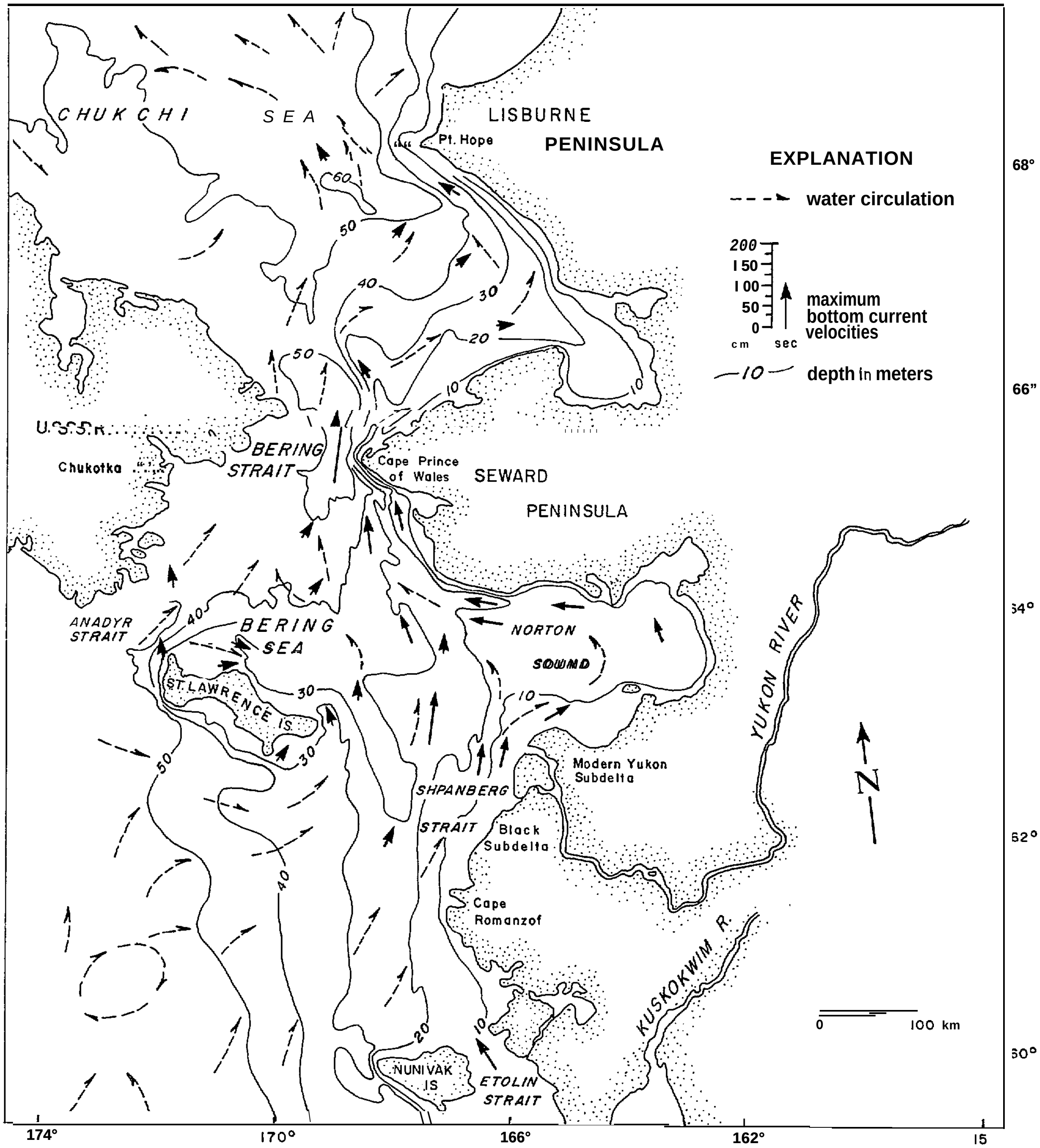
F. Radiograph showing shell and pebble storm lag layers near the surface and base of the core in addition to a series of thin sand layers (light colored) and parallel and lenticular bedding in the center of the core. Radiocarbon date at the core bottom is based on a piece of wood. Located 110 km from the Yukon Delta in 14 m water depth.

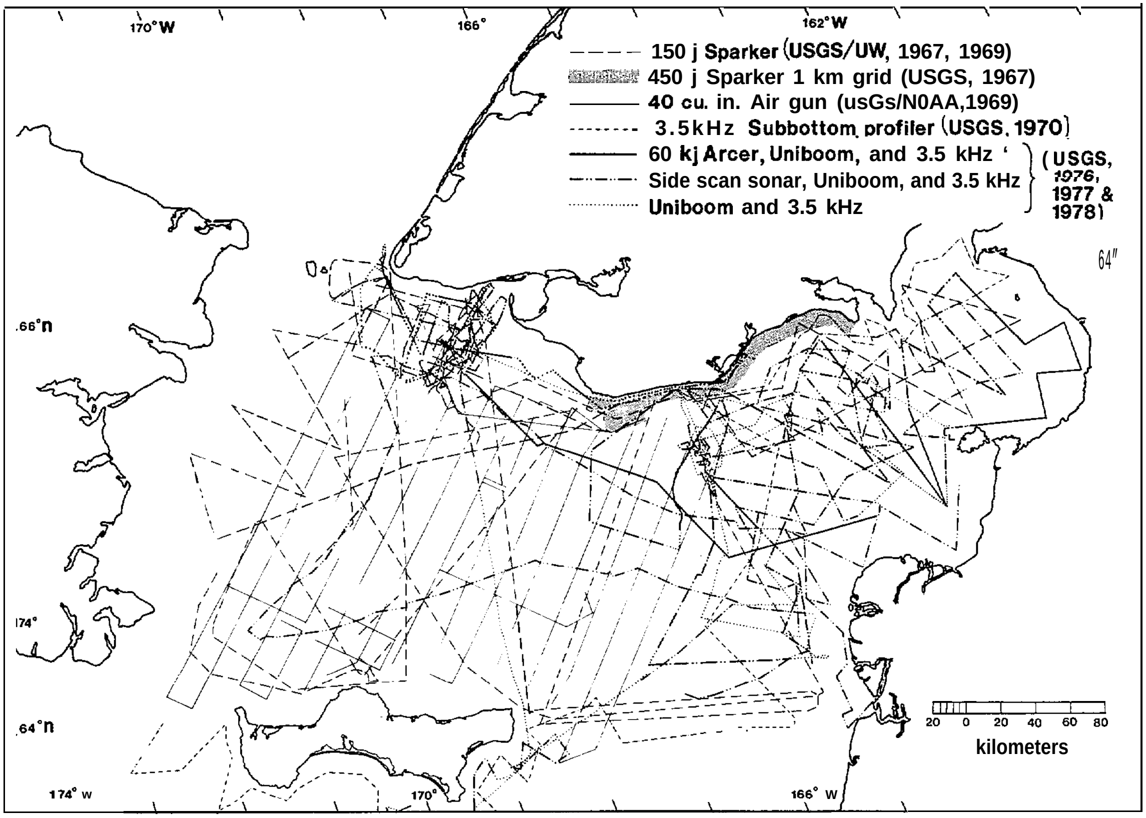
Figure 6. Preliminary map of the northeastern Bering shelf surficial geology.

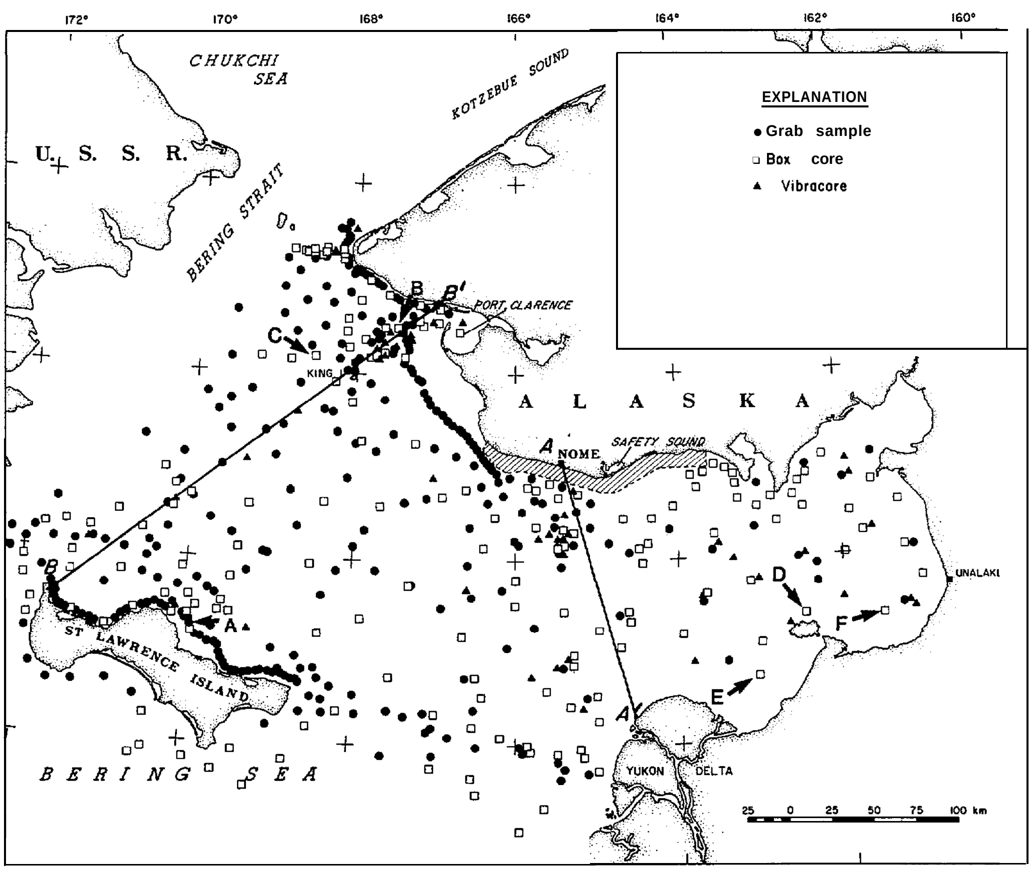
Figure 7. Conceptual model showing importance of physical structures versus biological structures in epicontinental shelf deltaic sequences (after Nelson et al., in press). Thickness of wedge depicts relative intensity of process from lower salinity and higher energy to higher salinity and lower energy shelf environments offshore. Relative thickness of storm sand sequences from inshore to offshore also is shown (Nelson, 1977). Area of thick storm sands and physical structures shifts seaward with influx of a prograding delta lobe and low-salinity water.

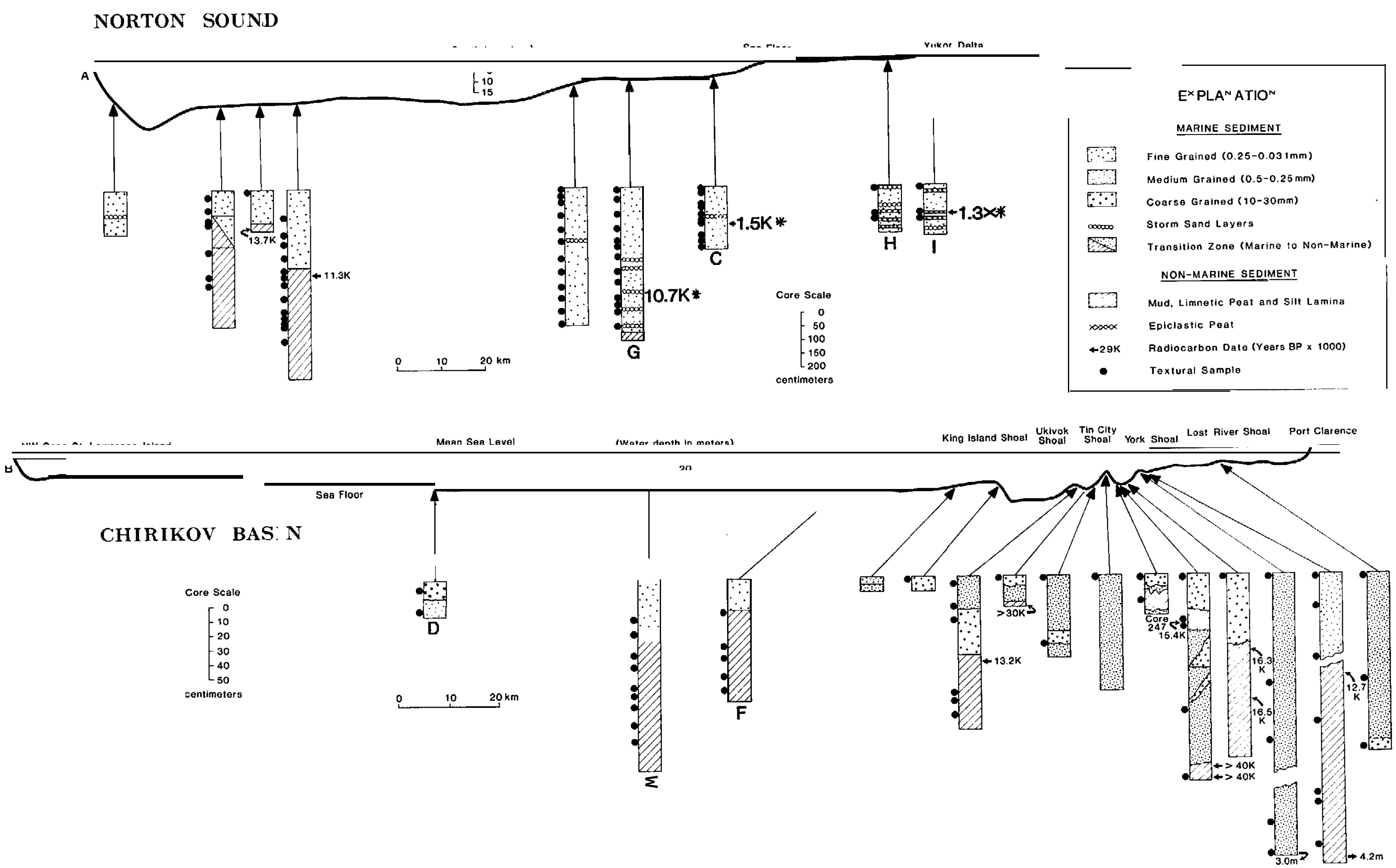
Figure 8. Transgressive sediment facies patterns based on grain-size modes (from McManus et al., 1977).

Figure 9. Generalized late Pleistocene and Holocene deposits of the eastern Bering Shelf, Alaska. Compiled from Gardner et al., (in press); McManus et al., (1977); Nelson and Creager, (1977); Knebel and Creager, (1973b); Nelson and Hopkins, (1972); Sharma et al., (1970).


CHUKCHI SEA
LISBURNE PENINSULA
Pt. Hope
EXPLANATION
water circulation
200
150
100
50
0
cm sec
maximum bottom current velocities
10 depth in meters
68°
66"
U.S.S.R.
Chukotka
BERING STRAIT
Cape Prince of Wales
SEWARD PENINSULA
ANADYR STRAIT
BERING SEA
NORTON SOUND
ST. LAWRENCE IS.
YUKON RIVER
Modern Yukon Subdelta
SHPANBERG STRAIT
Black Subdelta
Cape Romanzof
KUSKOKWIM R.
NUNIVAK IS
ETOLIN STRAIT
0 100 km
N
174°
170°
166°
162°
15
64°
62°
60°

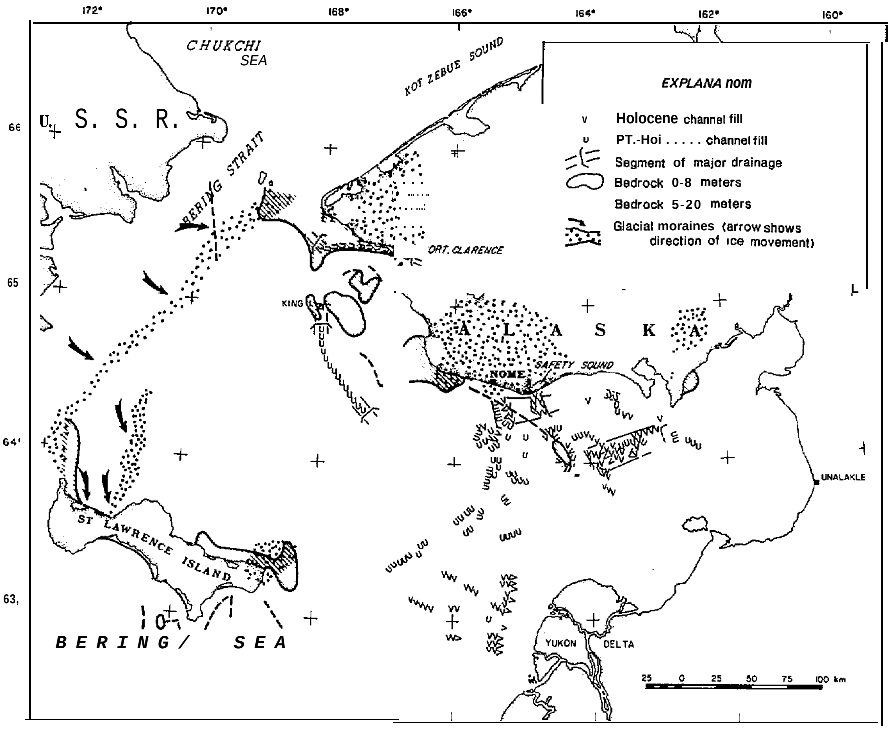

170°W
166°
162°W
150 j Sparker (USGS/UW, 1967, 1969)
450 j Sparker 1 km grid (USGS, 1967)
40 cu. in. Air gun (usGs/N0AA,1969)
3.5kHz Subbottom profiler (USGS, 1970)
60 kj Arcer, Uniboom, and 3.5 kHz
Side scan sonar, Uniboom, and 3.5 kHz
Uniboom and 3.5 kHz
(USGS, 1976, 1977 & 1978)
64"
66°n
174°
64°n
174° w
170°
166° W
20 0 20 40 60 80
kilometers


172°
170°
168°
166°
164°
162°
160°
CHUKCHI SEA
KOTZEBUE SOUND
U. S. S. R.
BERING STRAIT
66°
65°
64°
63°
EXPLANATION
Grab sample
Box core
Vibracore
B
B'
PORT CLARENCE
C
KING
A L A S K A
A
NOME
SAFETY SOUND
B
A
ST LAWRENCE ISLAND
D
F
UNALAKI
E
A'
YUKON
DELTA
BERING SEA
25 0 25 50 75 100 km



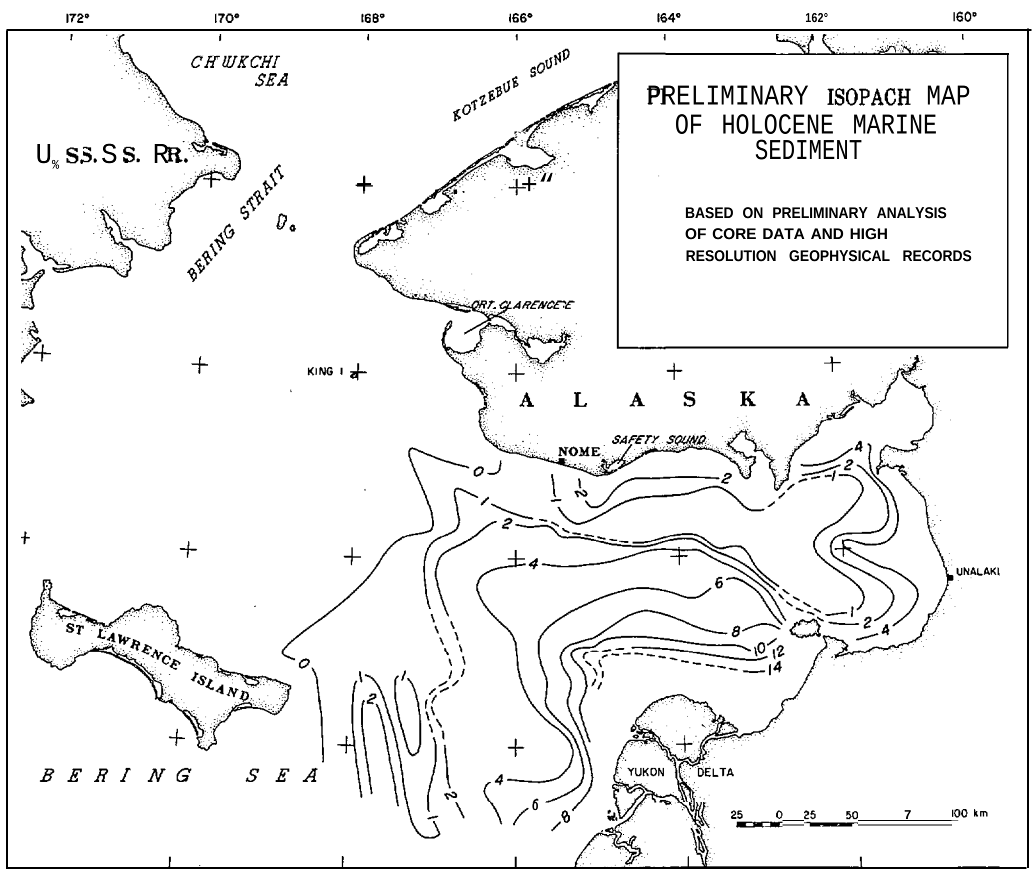
NORTON SOUND
Yukon Delta
A
10
15
13.7K
11.3K
10.7K*
G
1.5K*
C
H
1.3K*
I
0 10 20 km
Core Scale
0
50
100
150
200
centimeters
EXPLANATION
MARINE SEDIMENT
Fine Grained (0.25-0.031mm)
Medium Grained (0.5-0.25mm)
Coarse Grained (10-30mm)
Storm Sand Layers
Transition Zone (Marine to Non-Marine)
NON-MARINE SEDIMENT
Mud, Limnetic Peat and Silt Lamina
Epiclastic Peat
29K
Radiocarbon Date (Years BP x 1000)
Textural Sample
Mean Sea Level
(Water depth in meters)
20
B
Sea Floor
CHIRIKOV BASIN
Core Scale
0
10
20
30
40
50
centimeters
D
0 10 20 km
W
F
King Island Shoal
Ukivok Shoal
Tin City Shoal
York Shoal
Lost River Shoal
Port Clarence
13.2K
>30K
Core 247
15.4K
16.3 K
16.5 K
> 40K
> 40K
12.7 K
3.0m
4.2m

A

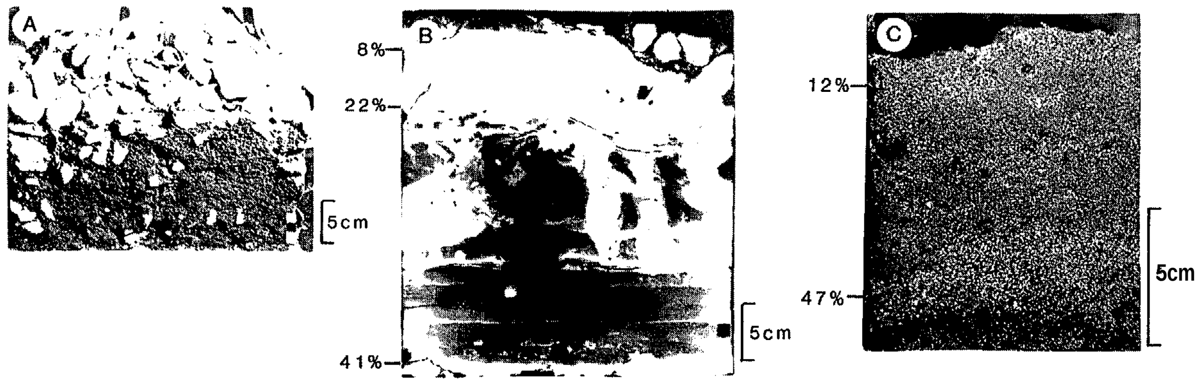


PRELIMINARY MAP OF SURFACE AND NEARSURFACE BEDROCK, GLACIAL MORAINES AND BURIED CHANNELS

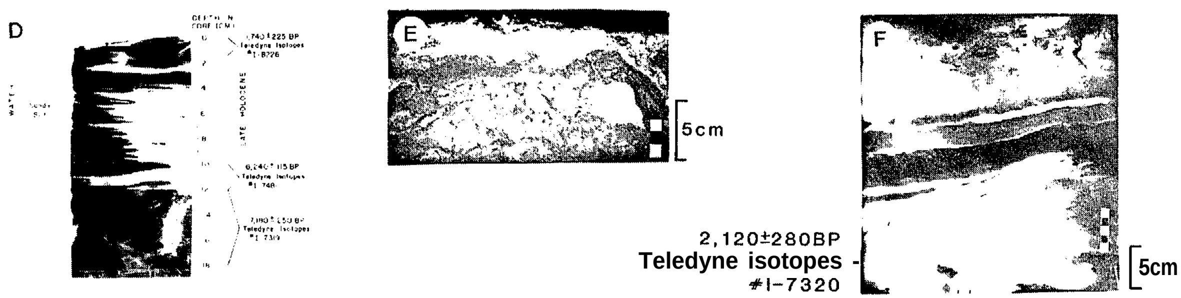
B

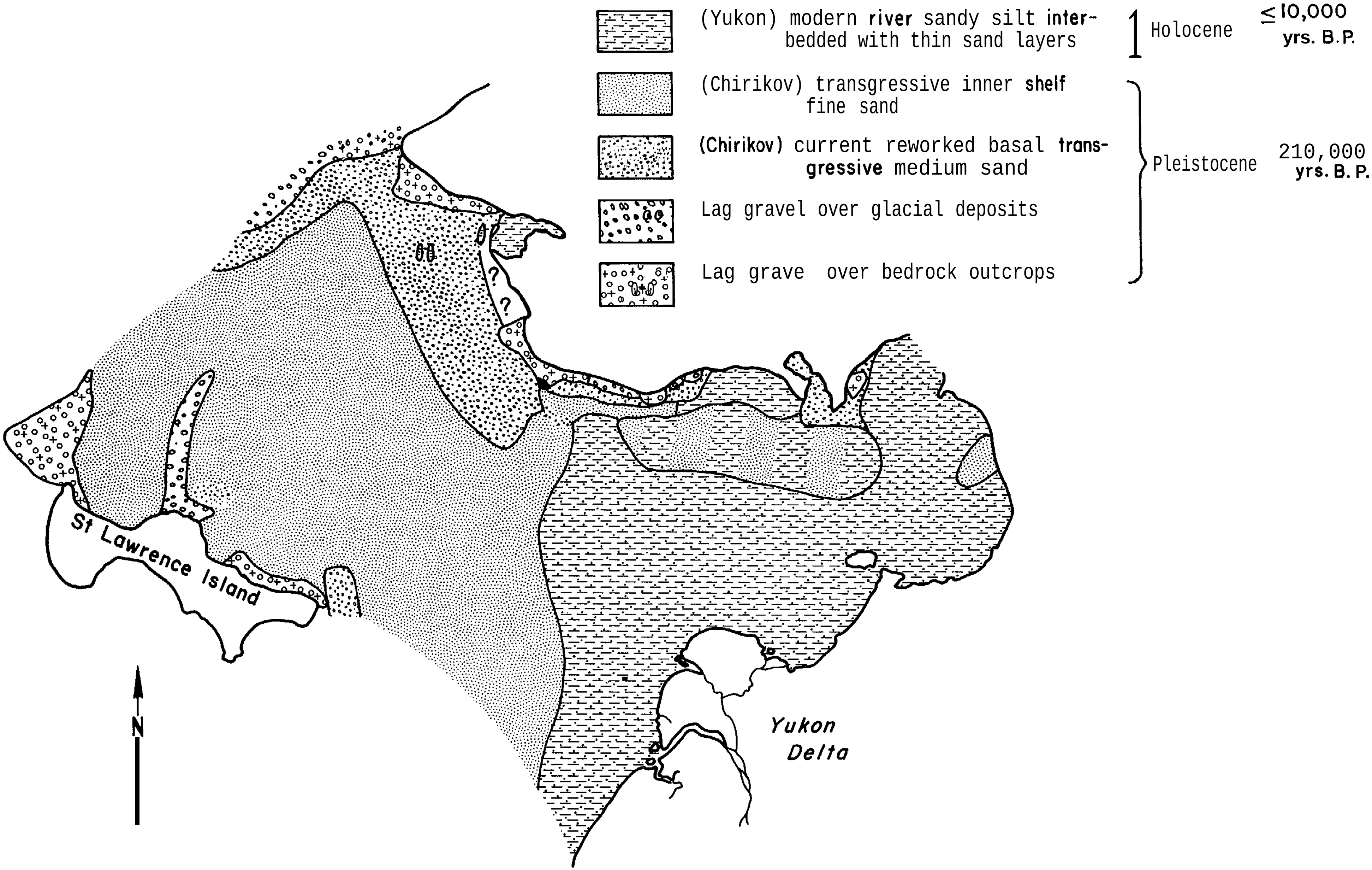


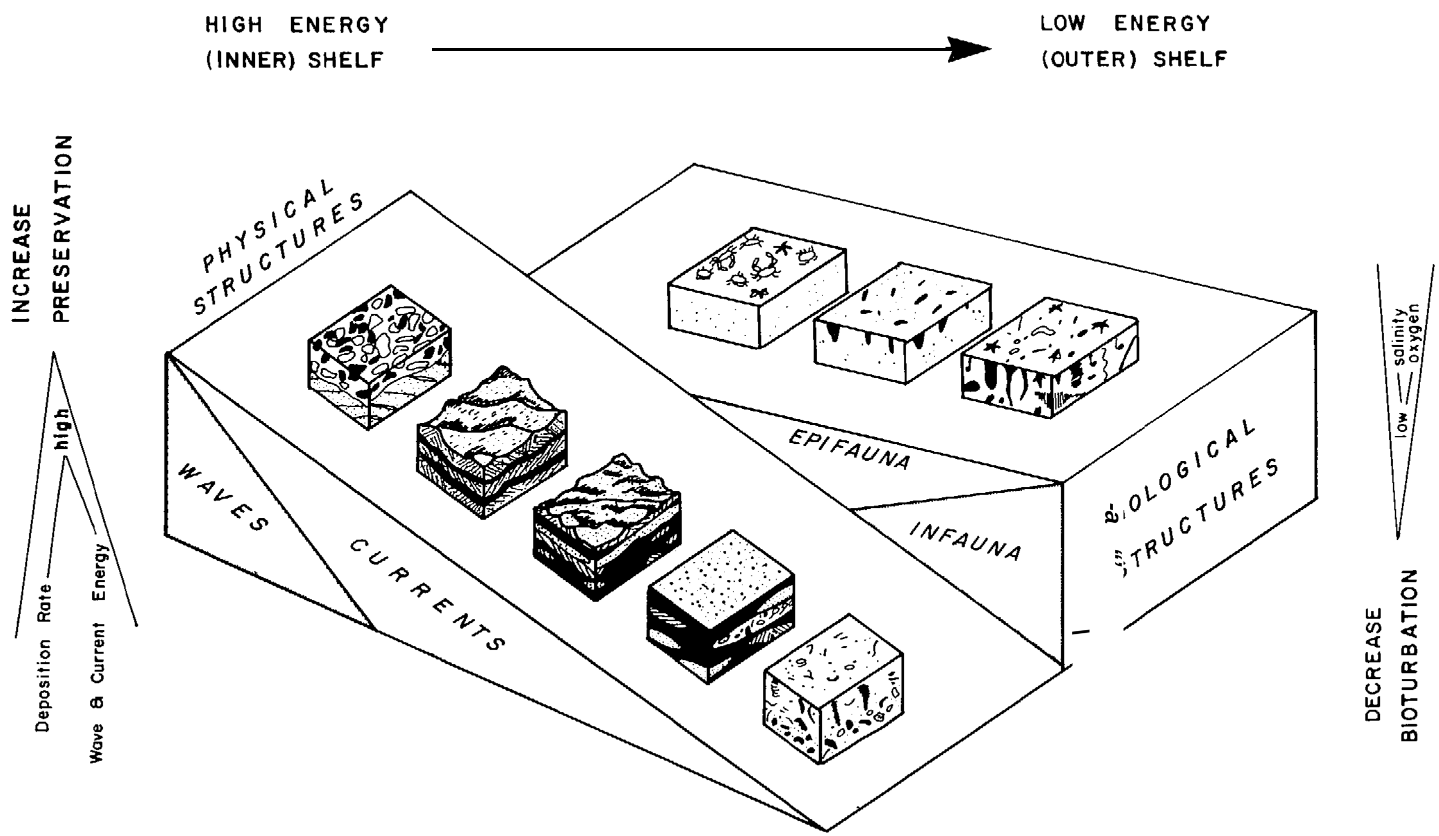
CHIRIKOV BASIN LATE PLEISTOCENE TRANSGRESSIVE DEPOSITS

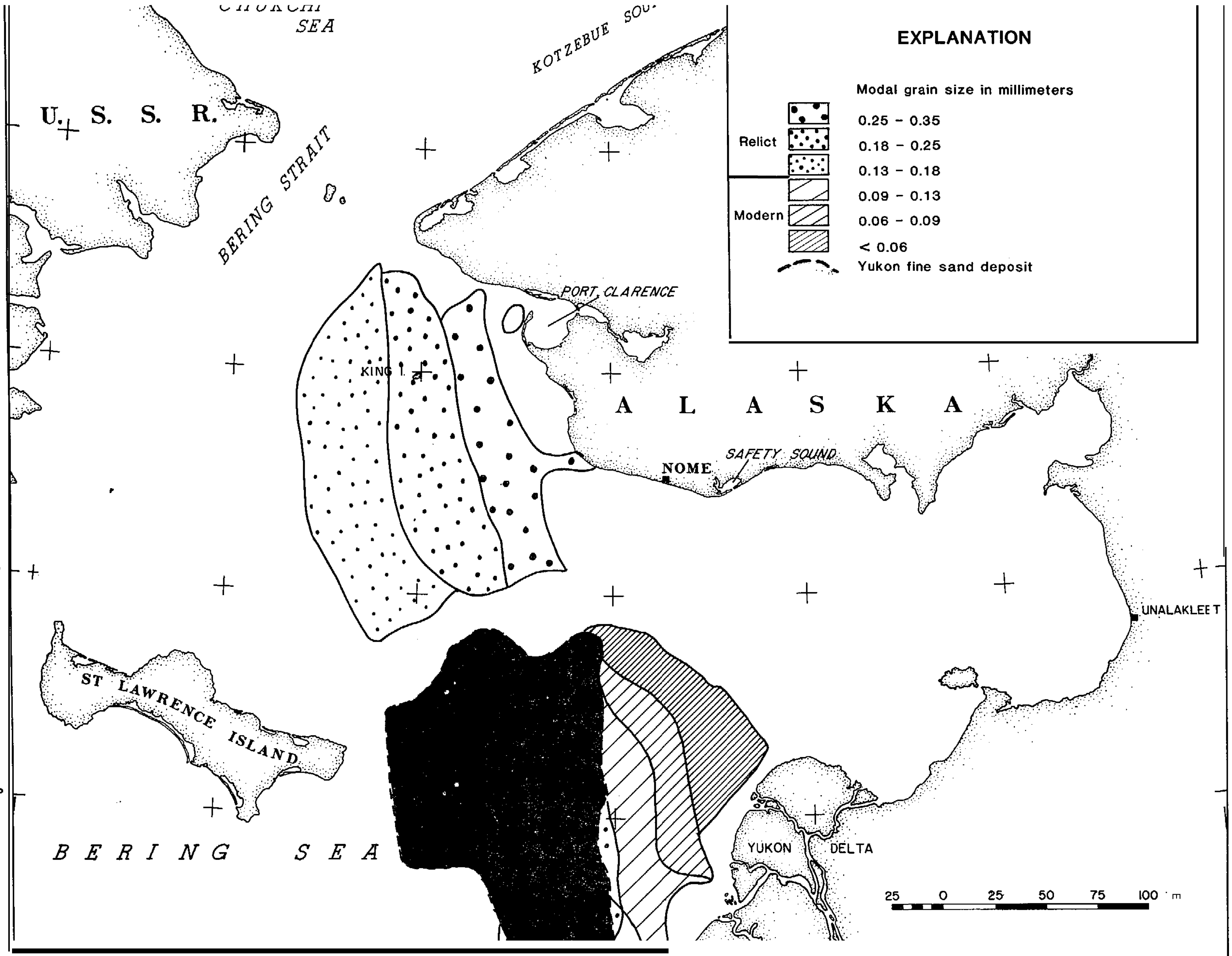


NORTON SOUND HOLOCENE DEPOSITS



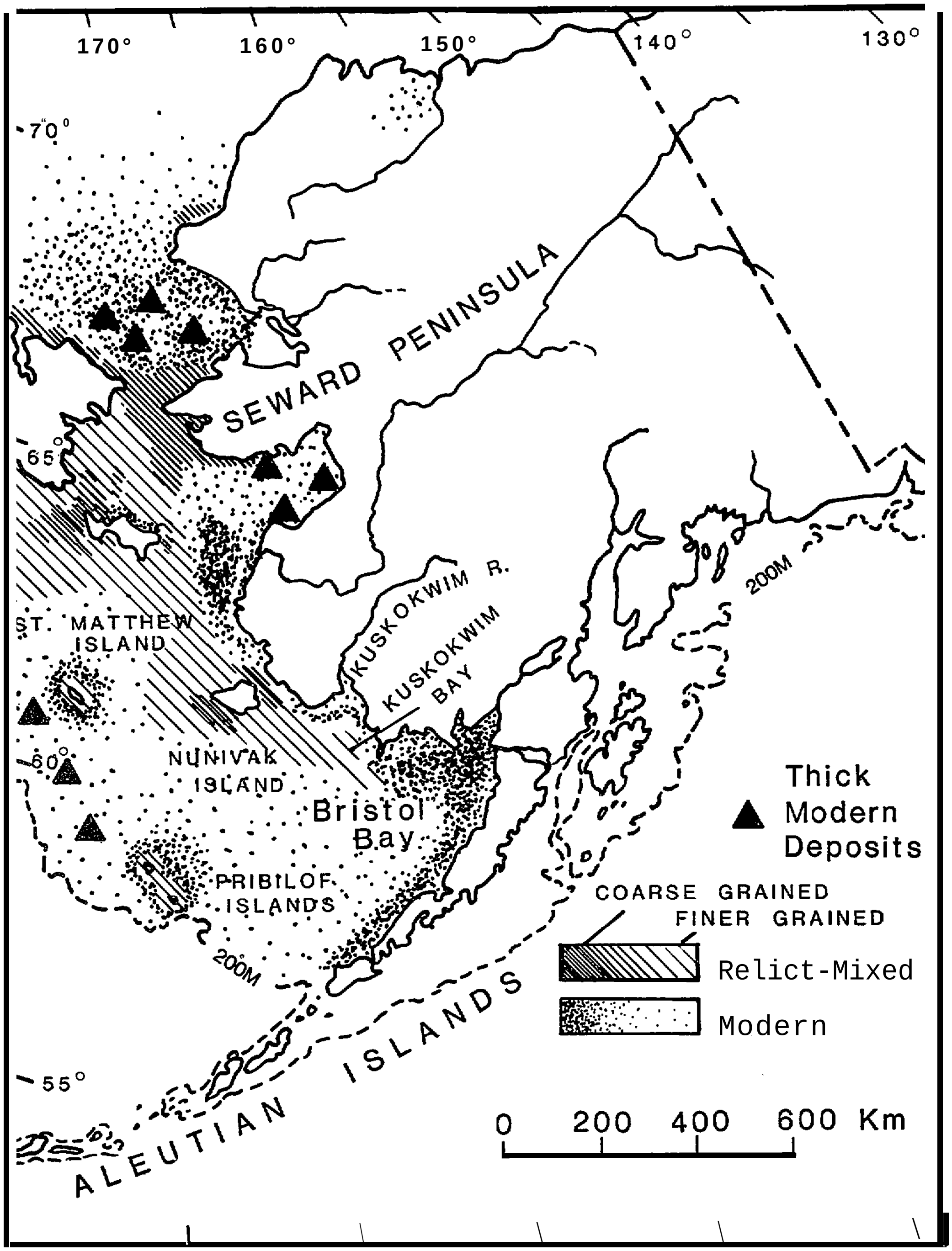

(Yukon) modern river sandy silt interbedded with thin sand layers
Holocene
≤10,000 yrs. B.P.
(Chirikov) transgressive inner shelf fine sand
(Chirikov) current reworked basal transgressive medium sand
Lag gravel over glacial deposits
Lag grave over bedrock outcrops
Pleistocene
210,000 yrs. B. P.
St Lawrence Island
Yukon Delta
N


HIGH ENERGY
(INNER) SHELF
LOW ENERGY
(OUTER) SHELF
INCREASE
PRESERVATION
high
Deposition Rate
Wave & Current Energy
PHYSICAL
STRUCTURES
WAVES
CURRENTS
EPIFAUNA
INFAUNA
BIOLOGICAL
STRUCTURES
low
salinity
oxygen
DECREASE
BIOTURBATION



PRELIMINARY ISOPACH MAP OF HOLOCENE MARINE SEDIMENT

BASED ON PRELIMINARY ANALYSIS OF CORE DATA AND HIGH RESOLUTION GEOPHYSICAL RECORDS



170°
160°
150°
140°
130°
70°
65°
60°
55°
SEWARD PENINSULA
KUSKOKWIM R.
KUSKOKWIM BAY
ST. MATTHEW ISLAND
NUNIVAK ISLAND
Bristol Bay
PRIBILOF ISLANDS
ALEUTIAN ISLANDS
200M
200M
Thick Modern Deposits
COARSE GRAINED
FINER GRAINED
Relict-Mixed
Modern
0 200 400 600 Km